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WASHINGTON DIVISION OF GEOLOGY AND EARTH RESOURCES
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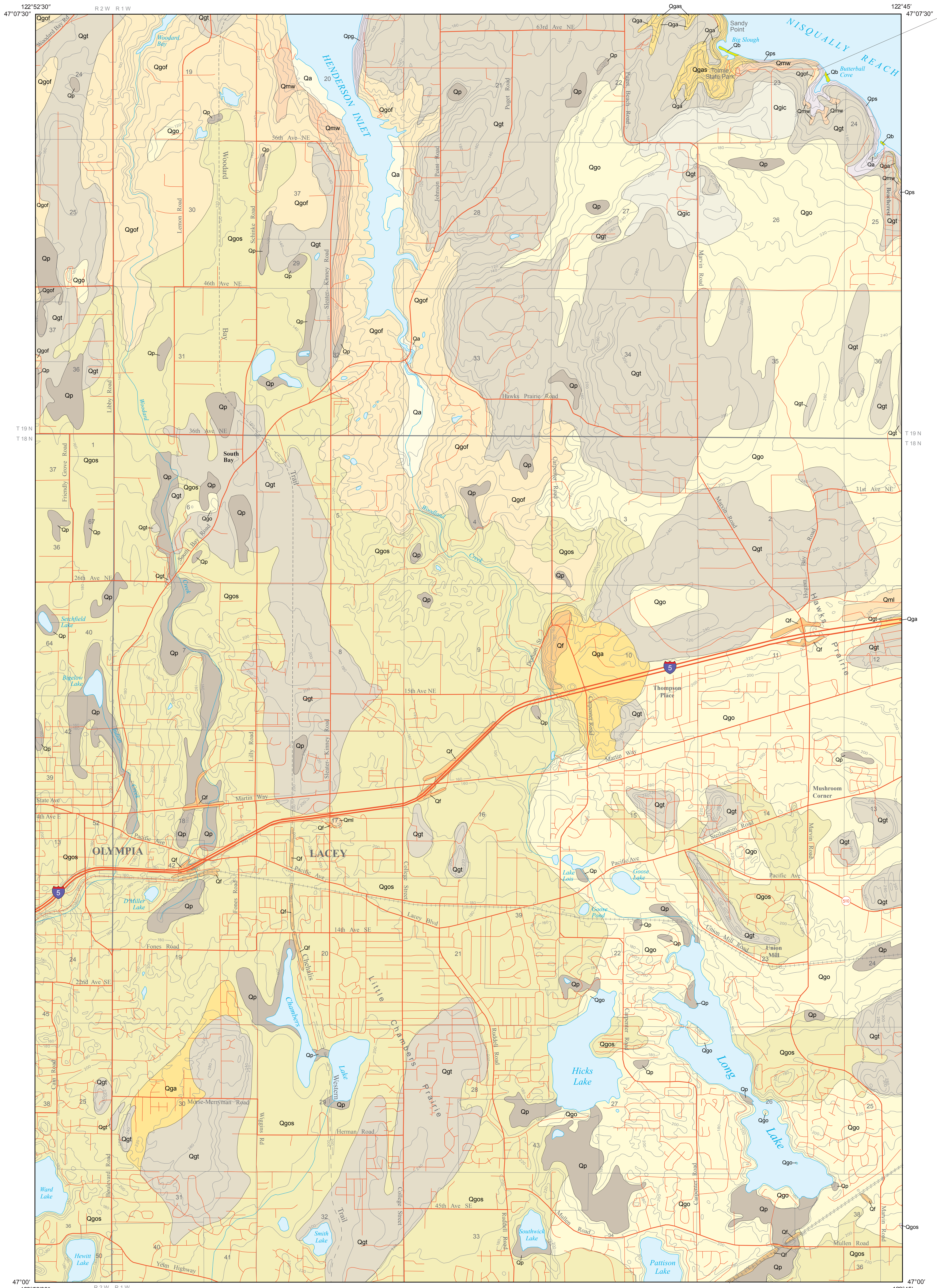

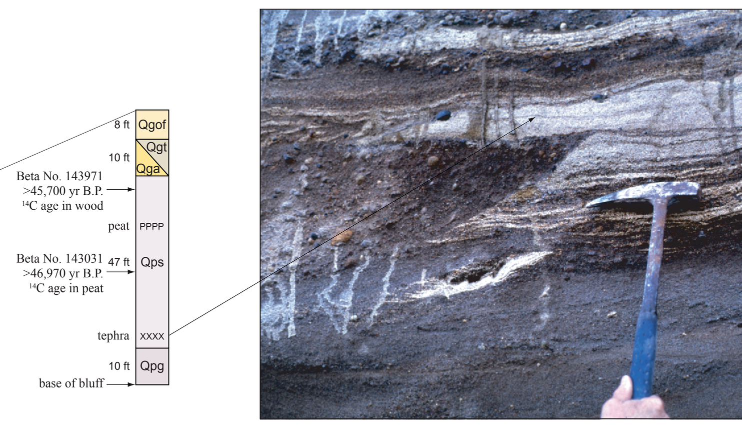

Figure 2. Outcrop of tephra interbedded with unit Qps at Butterball Cove. Chemical analysis at three different laboratories identified this tephra as probably from Mount St. Helens, although a specific match could not be positively identified.

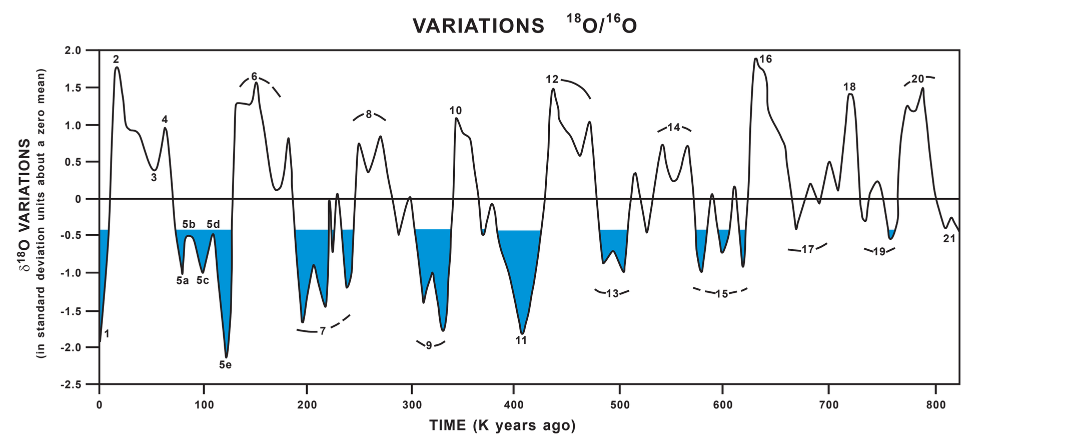

Figure 1. Marine oxygen-isotope stages (from Morrison, 1991). The numbers within the graph are stage numbers; the even-numbered peaks (at top) are glacial maxima and the odd-numbered troughs (at bottom) are interglacial minima. The blue areas indicate interglacial episodes, based on a cutoff at -0.5 $\delta^{18}O$ oxygen-isotope values (equivalent to Holocene interglacial values).

Geologic Map of the Lacey 7.5-minute Quadrangle, Thurston County, Washington

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INTRODUCTION

The Lacey quadrangle is located at the south end of Puget Sound in Thurston County and includes most of the city of Lacey and part of the city of Olympia. Land use is primarily urban, industrial, or low-density residential.

GEOLOGIC HISTORY

Late Wisconsinan–age Vashon Drift covers most of the quadrangle. Pre-Vashon units are generally exposed only along coastal bluffs, where mass wasting is common. Landslides and colluvium disrupt and obscure the continuity of exposures so that pre-Vashon geologic history is not easily deciphered. In the south Puget Lowland (south of Tacoma), all finite radiocarbon ages reported before 1966 are suspect due to laboratory contamination (Fairhall and others, 1966, p. 501). Stratigraphic assignments based on these invalid radiocarbon ages are now questionable and need to be re-evaluated. We have systematically sampled all datable material from nonglacial sediments subjacent to the Vashon Drift and found them to be older than previously reported. With a few exceptions, these sediments have been beyond the range of radiocarbon dating.

The antiquity of the pre-Vashon units causes radiocarbon dating to be of little help for making correlations, and abrupt facies changes within glacial and nonglacial units also render correlations tenuous. Despite these difficulties, we have developed a conceptual model for the more recent pre-Vashon geologic history that is consistent with our observations but by no means compelling.

The oxygen-isotope stage 4 glaciation, called the Possession Glaciation in the northern Puget Lowland, was mild relative to stages 2 and 6 (Mix, 1987; Fig. 1), which are represented in the Puget Lowland by the Vashon and Double Bluff Drifts respectively. The Possession ice sheet probably did not extend far south of Seattle (Lea, 1984; Troost, 1999). Because the ice sheet blocked drainage out of Puget Sound to the Strait of Juan de Fuca, a proglacial lake was impounded in most of the southern Puget Lowland. Streams flowing into this lake, such as the Nisqually, Puyallup, and Skokomish Rivers, formed an alluvial plain and deltas grading to lake level. These nonglacial sediments, deposited during stage 4, are all radiocarbon-infinite and overlie and interfinger with Possession outwash deposits. Once Possession ice no longer impounded the lake (but sea level was still significantly below modern sea level), existing drainages, such as the Nisqually and Puyallup Rivers, deeply and rapidly incised into their former alluvial plains and became entrenched. At least initially, stage 3, called the Olympia Interglaciation locally (Armstrong and others, 1965), was characterized by downcutting and erosion. As sea level began to rise, most deposition was confined to the entrenched channels. Because stage 3 sea level was probably about 100 ft lower than modern sea level (Ludwig and others, 1996, and references therein), stage 3 deposits were areally restricted. As Vashon ice advanced and sea level fell again at the beginning of stage 2, these rivers preferentially downcut in the same channels, eroding the late Olympia deposits so that finite-aged Olympia deposits would be rare above sea level.

As Vashon ice moved southward and grounded across the Strait of Juan de Fuca during stage 2, it dammed the northern outlet of the Puget Sound basin. Proglacial streams carried fluvial sediments southward into the Puget Lowland filling proglacial lakes and eventually the Puget Sound basin, first with silts, then sands and gravels. These sediments form the 'great lowland fill' of Booth (1994). Ice overrode these sediments, covering most of them with till, or scoured them away to deposit till directly onto pre-Vashon sediments. Subglacial channels were subsequently eroded into the fill. Proglacial lakes became impounded in these channels at different elevations above today's sea level as ice impinged on divides. The former lakebeds are presently the southernmost inlets of Puget Sound. (For a more thorough discussion of the subglacial channel network, see Booth, 1994, and Booth and Goldstein, 1994.) As these proglacial lakes spilled into lower-elevation basins and channels near the end of the Pleistocene, they deposited coarse, steeply dipping deltaic gravels along the margins of the channels and basins. Some of these deposits can be found near Steilacoom and Fort Lewis.

Much of the drainage originating from the ice sheet flowed southward and southwestward toward the Chehalis River. Some of the drainage probably occurred as glacial-lake outburst floods as valley-blocking ice dams breached during ice retreat. Deep troughs were carved out of the fill by subglacial fluvial erosion and extensive and complex terraces and braided channels were formed. As the ice receded, northward-flowing streams near Olympia filled the deep troughs with sandy sediments characterized by northward-directed paleocurrent indicators. These sediments provide evidence that drainage reorganized to flow northward through the recently formed outwash plain. The thickness of these sediments (unit Qgos) varies substantially throughout the area, reaching more than 400 ft just south of the map area at the Port of Olympia.

In the waning stages of the Fraser glaciation, glacial Lake Russell covered a large area of the southern Puget Lowland and deposited a relatively thin layer (1–10 ft) of fine grained varved sediments (unit Qgof) to an elevation of about 140 ft. These lacustrine silts (and rare clays and peats) commonly overlie unit Qgos sands and Vashon till (unit Qgt). Unit Qgos is important because it is widespread throughout the populous South Sound area and appears to behave differently from the rest of the Vashon Drift during earthquakes (Palmer and others, 1999a,b; Bodle, 1992; King and others, 1990).

The oxygen-isotope stage 6 glaciation, called the Double Bluff Glaciation in northern Puget Sound, was probably as extensive as the stage 2 or Vashon Stade of the Fraser Glaciation (Mix, 1987; Fig. 1). The end moraines of this glaciation lie a short distance beyond the inferred limit of the Vashon ice in the vicinity of Tenino (Lea, 1984). Subglacial erosion was probably similar to the erosion that Booth (1994) documented beneath Vashon ice and would have left more accommodation space for deposition during the interglacial time of oxygen-isotope stage 5. For pre-Vashon nonglacial deposits that are radiocarbon-infinite, therefore, it is difficult to distinguish deposits of stage 3 from deposits of stage 5, and we have not attempted to do so in the present mapping.

In some outcrops, however, tephras are present that provide a tool for geochemical correlation to known eruptions of nearby Cascade stratovolcanoes. A tephra found at Butterball Cove in sec. 19, T19N R1E (Fig. 2) has been tentatively correlated geochemically to Mount St. Helens (Franklin F. Foit, Jr., Wash. State Univ.; Andrei M. Sarna-Wojcicki, U.S. Geological Survey; Thomas W. Sisson, U.S. Geological Survey, personal communs., 2000–2002). At present, this tephra has not been correlated to a specific eruption, but we have found it at several other localities in southern Puget Sound. Tephra correlations appear promising but will require more data.

PREVIOUS GEOLOGIC MAPPING

The glacial history and geology of south Puget Sound are well-summarized by Bretz (1913), who mapped the entire Puget Sound basin in reconnaissance. Noble and Wallace (1966, 1:72,400) produced small-scale water resources studies. The Coastal Zone Atlas (Washington Department of Ecology, 1980) provides mapping of a 2000-ft-wide strip along the shoreline at a scale of 1:24,000. Walsh (1987), Walsh and others (1987), and Palmer and others (1999a) compiled and augmented previous mapping.

MAPPING METHODS

For the present map, we inspected available construction site excavations, gravel pits, and roadcuts. We surveyed the shorelines by boat and took samples and measured sections at cliff exposures. Contacts between map units are commonly not exposed and are only approximately located. They are generally located by outcrop mapping, air photo and lidar interpretations, interpretations of water well logs from Washington Department of Ecology files, and, in part, modified from Drost and others (1998). USDA soil maps (Pringle, 1990) helped guide the location of peats and the contacts between sandy and gravelly units. Location accuracy of contacts is judged to be about 200 ft in general. Contacts between some units are gradational. We have tried to consider geotechnical significance in mapping geological units and have attempted to show units only where they are thicker than 5 to 10 ft or mask the underlying lithology.

ACKNOWLEDGMENTS

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DESCRIPTION OF UNITS

Quaternary Unconsolidated Deposits

HOLOCENE NONGLACIAL DEPOSITS

Qf — **Fill**—Clay, silt, sand, gravel, organic matter, rip-rap, and debris; includes engineered and non-engineered fills; shown only where fill placement is extensive, sufficiently thick to be of geotechnical significance, and readily verifiable.

Qml — **Modified land**—Soil, sediment, or other geologic material that has been locally reworked to modify the topography by excavation and (or) redistribution.

Qa — **Alluvium**—Silt, sand, gravel, and peat deposited in stream beds and estuaries; may include some lacustrine and beach deposits.

Qb — **Beach deposits**—Mud and sand deposited in the intertidal zone or residual gravel on a wave-cut platform.

Qmw — **Colluvium**—Loose soil and glacial sand and gravel deposited by soil creep and shallow ravelling on hillslopes, some of which occurred during the waning stages of the Vashon Stade of the Fraser Glaciation. Shown where colluvium is of sufficient thickness to mask underlying geologic strata.

Qp — **Peat**—Organic and organic-matter-rich mineral sediments deposited in closed depressions; includes peat, muck, silt, and clay in and adjacent to wetlands.

PLEISTOCENE GLACIAL DEPOSITS

Deposits of Continental Glaciers—Cordilleran Ice Sheet

VASHON STADE OF THE FRASER GLACIATION

Glacial sediments described in this section consist mostly of rock types of northern provenance, most from the Canadian Coast Range. A wide variety of metamorphic and intrusive igneous rocks not indigenous to the Puget Lowland and generally southerly directed current indicators help distinguish these materials from the volcanic-lithic-rich sediments of the eastern Puget Lowland and the Crescent Basalt/Olympic Core-rich sediments of the western Puget Lowland.

Qgof — **Latest Vashon fine-grained sediments**—Lacustrine clayey and (or) fine sandy silt with sparse, disseminated dropstones; laminated and commonly vertically jointed; medium gray where fresh to pale yellow where dry and oxidized. In both fresh and oxidized exposures, this unit is distinguished by relatively darker (chocolate brown in oxidized exposures) horizontal bands about 1 in. thick that may represent annual winter depositional layers in a varve sequence; no more than about 20 apparent varves were counted in any exposure, suggesting a short life for the glacial lake(s) in which unit Qgof was deposited; present in deposits ranging up to 10 ft thick over much of southern Puget Lowland and most commonly found at elevations below about 140 ft; mapped where it is thought to be at least about 5 ft thick or where it masks the underlying geomorphology; includes deposits of glacial Lake Russell and other lakes of the Vashon glacial recession.

Qgos — **Latest Vashon recessional sand and minor silt**—Moderately well-sorted, moderately to well-rounded, fine- to medium-grained sand with minor silt; noncohesive and highly permeable; thickness inferred from wells reaches up to 100 ft; deposited in and around the margins of glacial lakes; surrounds numerous steep-walled lakes and depressions (kettles), evidence that this unit was largely deposited during deglaciation when there was stagnant ice occupying much of the southern Puget Lowland.

Qgo — **Vashon recessional outwash**—Recessional and proglacial stratified, moderately to well-rounded, poorly to moderately sorted outwash sand and gravel of northern or mixed northern and Cascade source, locally containing silt and clay; also contains lacustrine deposits and ice-contact stratified drift. Some areas mapped as unit Qgo may instead be advance outwash (unit Qga), as it is difficult to tell the difference between the two without the presence of an intervening till.

Qgt — **Vashon till**—Unstratified and, in most exposures, highly compacted mixture of clay, silt, sand, and gravel deposited directly by glacier ice; gray where fresh and light yellowish brown where stained; unsorted and, in most exposures, of very low permeability; most commonly matrix-supported but may be clast-supported; matrix generally has a more gritty feel than outwash sands when rubbed between fingers, due to being more angular than water-worked sediments; cobbles and boulders commonly faceted and (or) striated; ranges in thickness from wispy, discontinuous layers less than 1 in. to more than 30 ft thick; thicknesses of 2 to 10 ft are most common; mapped till commonly includes outwash clay, silt, sand, gravel, or ablation till that is too thin to substantially mask the underlying, rolling till plain; erratic boulders are commonly associated with till plains but may also occur as lag deposits where the underlying deposits have been modified by meltwater; typically, weakly developed modern soil has formed on the cap of loose gravel, but the underlying till is unweathered; local textural features in the till include flow banding and apophyses commonly extending 10 to 15 ft downward into underlying sand and gravel that are oriented transverse to ice flow direction.

Qgic — **Ice-contact deposits**—Mix of deposits from undifferentiated dynamic ice and dead ice. Dynamic ice deposits include lodgment till, drumlins, and advance outwash; dead-ice deposits include ablation till, subglacial water flow deposits (such as eskers), and recessional outwash; typically lacks thick, continuous, or widespread deposits of lodgement till at the ground surface, though small till exposures and detrital till fragments are common; topography formed by a mix of subglacial, ice-marginal, and recessional processes.

Qga, Qgas — **Vashon advance outwash**—Sand and gravel and lacustrine clay, silt, and sand of northern or mixed northern and Cascadian source, deposited during glacial advance; locally contains nonglacial sediments, typified by silt rip-ups, cobbles, and peat rip-ups as lag along channel sides and bottoms; gray where fresh, light yellowish gray where stained. Sands (unit Qgas) are commonly thick (locally 100 ft), well sorted, and fine to medium grained, with lenses of coarser sand and gravel, locally called Colvos Sand (Garling and others, 1965); generally permeable and porous with low cohesivity relative to both overlying till and underlying pre-Vashon sediments; prone to deep-seated landsliding where it overlies relatively impermeable and more compact clay- or silt-rich units.

PLEISTOCENE DEPOSITS OLDER THAN VASHON DRIFT

Qps — **Pre-Vashon sand-size or finer deposits**—Massive to cross-bedded sand interbedded with laminated silt and minor peat, diatomite, and gravel; immediately subjacent to Vashon Drift and generally overlying unit Qpg. This unit is thought to be of nonglacial origin, and is dominated by varied Cascade-source volcanic lithic rock types. These sediments have previously been referred to the Kitsap Formation and were inferred to be of Olympia age, although all known deposits in the south Puget Lowland are older than the type section of the Olympia nonglacial interval (Armstrong and others, 1965) and most are radiocarbon-infinite or suspect. Two radiocarbon samples were obtained from the cliff exposure that is detailed in the stratigraphic column next to Figure 2. Deeter (1979) has shown that the type locality of the Kitsap Formation includes radiocarbon-infinite sediments of both glacial and nonglacial origin, and we follow his suggestion that the name be abandoned. Because we cannot establish that all pre-Vashon nonglacial sediments are correlative, we have chosen not to assign them a stratigraphic name.

Qpg — **Pre-Vashon gravel**—Gravel and sand, generally of mixed northern and Cascade Range provenance; moderately to poorly sorted; commonly cross bedded but may lack primary sedimentary structures; commonly tinted orange with iron-oxide staining; stratigraphically underlying the Vashon Drift; most commonly exposed immediately beneath exposures of unit Qps; gravelly portions of unit Qpg are relatively resistant to erosion; inferred to be of glacial origin because interglacial conditions do not appear conducive to streams with sufficient competency to deposit widespread gravels in most of the Puget Lowland and because the majority of the exposures include northern-source metamorphic rock clasts.

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Lambert conformal conic projection
North American Datum of 1927
Base map information from the Washington Department of Natural Resources, Geographic Information System, and from U.S. Geological Survey digital line graphs.
Digital cartography by Charles G. Caruthers, Anne C. Heinitz, and J. Eric Schuster.
Editing and production by Jaretta M. Roloff and Karen D. Meyers.

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